Optimising flax production in the South Atlantic region of the USA

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Abstract: Worldwide the USA is the largest user of flax fibre, though very little is actually grown or produced in the USA. 'Ariane' flax was grown in 1990–1991, 1991–1992 and 1998–1999 in South Carolina, USA and evaluated for production characteristics. Plots (15 m long and 2 m wide) in the fall of 1990 and 1991 generated dry matter plant yields ranging from 4510 (early harvest at a seeding rate of 67 kg ha^{-1}) to 7340 (late harvest at a seeding rate of 134 kg ha^{-1}) kg ha^{-1}. Based on these results, seed was sown on a private farm using a drill in 19 cm rows at a seeding rate of 101 kg ha^{-1} in 1998–1999. Early harvest, selected for optimal fibre quality, produced a dry matter plant yield that averaged 4076 kg ha^{-1}. Late harvest, selected to optimise seed plus fibre, produced a dry matter plant yield that averaged 5076 kg ha^{-1}. Stubble remaining in the field after mowing at about 6.0–7.6 cm above the soil surface resulted in a fibre loss of about 3% of total plant dry matter or 10% of potential total fibre yield. Dry matter and fibre yields suggested that flax could be produced in the southeastern USA using traditional farming methods for the area.
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INTRODUCTION

Flax (*Linum usitatissimum* L) production in the South Atlantic region has the potential to provide income to farmers and to supply a domestic source of flax to the fibre industries of the USA. Flax is best adapted to cool and moist climates.[1,2] In the southeastern USA the warm winter climate allows this crop to be grown during the winter months on traditionally dormant fields or to double crop for higher economic benefits. While flax has been produced and studied for decades in South Carolina as a low-value fibre crop for pulp (Frederick J, *et al*, 1999, unpublished), the properties of flax fibre make it suitable for high-value products such as textiles and composites. Growing conditions should be considered when developing a manufacturing process to produce fibres of uniform colour, size, shape and fineness.

Frost or drought can damage flax development, so proper planting times are necessary to optimise fibre yields and quality. The optimum flax planting period along the coast in South Carolina is between 20 October and 10 November to obtain the benefit of cool, wet weather.[3] Sharma and Van Sumere[1] reported that, for maritime areas, rainfall should be evenly distributed throughout the flax growing season, totalling approximately 700 mm, to fulfil the crop's water requirement. Robinson[4] indicated that superior fibre flax crops are grown when 84–96 kg seed ha^{-1} is planted at a proper planting time, while Parks *et al*[3] reported that 124 kg ha^{-1} is the desired seeding rate for South Carolina.

Flax is considered a clean-up crop in rotation, because herbicides can be used to control weeds not easily controlled in cereal crops.[5] A well-prepared field is required, because flax grows from small seeds planted only 1.3–2.0 cm deep. Initially, flax does not compete well with other plants, and yield and quality are improved with weed control.[6] To obtain good seedling emergence and high flax yields, seedbed preparation is more important than with most small grains. The best results occur when the field is level so that uniform seed placement occurs. The growing season in South Carolina for fall-planted fibre flax ranges from 140 to 225 days. Flax harvested early with immature seed production produces fine, soft fibres lower in strength and yield, whereas fibres from mature flax harvested later for seed are coarse and brittle.[7] Ideal fibre characteristics vary according to end use and include fibre homogeneity, divisibility and variety.[8] Retting techniques and climatic conditions also influence fibre quality.[8]

High-quality, short-staple 'cottonized' fibres from early-harvested flax, or ideally from flax harvested for

both seed and fibre, could be used for blending with cotton and other textile fibres. Canadian farmers now growing flax seed manage their waste flax straw by either spreading chopped flax straw directly on their land, bunching and burning flax straw, using flax straw as ruminant livestock feed, or baling the flax straw for fibre flax processing.[5] In Canada, about 15–20% of the straw from commercial flax seed production is used for speciality (mostly cigarette) paper.[9] Prior studies show that fibre flax can be produced in the South Atlantic region,[3,10] but research is needed to determine optimum production practices. The objective of this study was to grow flax as a winter crop to investigate the influence of production practices and harvest date on yield and stem characteristics.

MATERIALS AND METHODS

'Ariane' flax was grown in northeastern South Carolina as a winter crop. This variety was selected for the study because of its high straw yield in Europe[8] and the southeastern USA (Frederick J, 1990, unpublished) compared with other straw-type flax varieties. In 1990–1991 and 1991–1992, crops were grown in small plots; in 1998–1999, flax was evaluated on a private farm that used commercial equipment for planting, harvesting and baling.

Plots were planted in the fall of 1990 and 1991 in Darlington County at the Pee Dee Research and Education Center located near Florence, SC (latitude 34° 17′ N and longitude 79° 41′ W). The soil was Norfolk loamy sand (fine-loamy, siliceous, thermic Typic Kandiudult) and the previous crop was maize.

In 1990–1991 and 1991–1992, treatments were arranged as a randomised complete block with four replications for both the spring N rate and seeding rate studies. Plots were 15.2 m long and eight rows wide. Rows were spaced at 20 cm. The studies were located adjacent to each other and received the same land preparation. Soil preparation included discing twice to a depth of 15 cm and chisel ploughing at right angles to a depth of 30 cm. Trifluralin (trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine) was applied before planting at a rate of 1.12 kg ha^{-1} and incorporated with a field cultivator. Bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) was broadcast applied in mid-January to all plots in both years at a rate of 0.43 kg ha^{-1}. Fertiliser (of fertiliser grade 0-9-18) was applied at a rate based upon soil test results and Clemson University Cooperative Extension Service recommendations for small-grain production, providing 148.8 kg potassium and 39.2 kg phosphorus ha^{-1}. All plots received 28 kg N ha^{-1} applied just prior to planting as ammonium nitrate using a 1.8 m long Gandy 1006T fertiliser spreader (Gandy Co, Owatonna, MN, USA). Planting dates were 29 October and 27 October in 1990 and 1991 respectively. Flax was planted using an eight-row Hege 1000 grain seeder (Hege Equipment Inc, Colwich, KS, USA) equipped with press wheels. For the seeding rate

study, flax was planted at seeding rates of 67, 101 and 134 kg ha^{-1}. For the spring N rate study, flax was planted at a seeding rate of 112 kg ha^{-1}. Spring N was applied on 4 and 9 February in 1991 and 1992 respectively as ammonium nitrate using a 1.8 m wide Gandy fertiliser spreader. Spring N was applied to flax in the seeding rate study at a rate of 56 kg ha^{-1}. Flax in the spring N rate study received N rate treatments of 0, 29, 56 and 84 kg ha^{-1}.

Flax plants from both studies were sampled at the onset of flowering for straw yield on 28 March in 1991 and 31 March in 1992. Two 1 m long samples selected at random were hand harvested 2.5 cm above the soil surface. Samples were bagged, dried at 70 °C for 48 h and weighed. Four 1 m long samples were also hand harvested from each plot when 90% of the seed bolls had turned brown (seed maturity—3 June in 1991 and 28 May in 1992). These samples were also dried at 70 °C for 48 h, the seed was threshed and the straw was re-dried for 24 h and weighed. Canopy height was measured at two random locations in each plot immediately prior to the harvest at seed maturity.

In 1998–1999, 'Ariane' flax seed was planted on a private farm, latitude 33° 35′ N and longitude 79° 34′ W, near Nesmith, SC in Williamsburg County. The elevation of the flax field was approximately 21 m above sea level. Previously the field had been planted with tobacco. A preliminary soil test on the field indicated a pH of 5.8. The flax field was located on gently sloping Eunola or Emporia loamy sand.[11] The soil is a loamy or silty clay soil having good internal drainage and 0.5–2% organic matter.[11]

As briefly outlined by Foulk et al,[12] the seedbed was prepared in 1998–1999 using an 8.23 m International 3900 disc harrow and a Perfecta II 4.57 m Unverferth field cultivator. Granular fertiliser (of fertiliser grade 3-5-32) was applied at a rate of 450 kg ha^{-1} on 1 November 1998 prior to field discing, providing 13.3 kg nitrogen, 22.5 kg phosphorus and 143.6 kg potassium ha^{-1}. No pre-plant herbicide was added to the field. The seeding date was delayed until 15 December 1998 owing to dry conditions not considered optimal for flax germination. The seeding depth was less than 0.6 cm, with a drill spaced 19 cm apart and with no press wheels for soil firming. Flax seed was planted at 101 kg ha^{-1}. In February, 1871 l ha^{-1} of 25S (25% nitrogen and 3% sulphur) was broadcast by a pull-type applicator and provided 55.1 kg nitrogen and 7.2 kg sulphur ha^{-1}. No other treatments were applied to the field.

Flax planted on the commercial farm employed in 1998–1999 was originally intended to give two harvests: (1) young plants providing optimal fibre, and (2) mature plants providing both seed and fibre. Once the plants emerged and reached a height of a few cm, however, large variations were observed in the colour, vigour and height of plants within particular areas of the field. These areas had not been laid in replicated plots for statistical comparisons, but nonetheless they afforded an opportunity to characterise plants of one

cultivar produced under different (albeit undefined) conditions grown for two stages of maturity. Therefore the field was divided into four 0.5 ha zones by visually rating the plants based on colour, vigour and height. Further, each zone was subdivided into two side-by-side portions (matched regions 1, 5; 2, 6; 3, 7; and 4, 8) for an early harvest (regions 1–4) of young or late harvest (regions 5–8) of mature plants. Since the differences were remarkable, the soil was analysed postharvest to evaluate differences in soil conditions.[13] Stalk yield and plant characteristics were recorded for each region and stage of maturity, with results provided from individual regions and averages for young and mature plants.

Flax as an early crop for fibre, with attached immature seeds, was harvested on 5 May 1999, and as a late, mature crop was harvested on 27 May 1999 for both seed and fibre production. Samples (11 kg) of early-harvested flax were manually removed from the field and placed in an enclosed building with ventilation for drying. Straw remaining in the field was dried or dew retted prior to baling. Dew retting is dependent upon weather conditions and is completed in a week (weather warm and moist) to months (weather cold and dry). In this process, indigenous fungi and bacteria partially decompose the pectinaceous and matrix substances to separate cellulose fibres from the woody portion of the flax plant. Both harvests of flax were cut using a drum mower (Fella Werke, Feucht, Germany). For the late harvest of flax, seeds were first removed from stalks with a Shelbourne–Reynolds stripper header (Colby, KS, USA) attached to a CASE IH (International Harvester, Racine, WI, USA) combine. After stripping, the flax was mowed and evenly spread across the soil surface using an HSR rake (JF Fabriken, Sonderborg, Denmark) and allowed to dry. Flax was baled using a CASE IH baler.

Flax plants in 1998–1999 from three separate rows each 0.9 m long were pulled from the soil, bundled together and oven dried in the laboratory. The 1998–1999 flax plant yield was based on the dried weight of the entire flax stalk including roots and seeds.

Stubble height in 1998–1999 was measured across the entire region (one measurement per row) to sample the entire cross-section of the field. Flax stubble with roots attached was excavated from three separate areas of each mowed region along one row in 30.5 cm sections for laboratory assessment. The three stubble samples from each region were combined and air dried. From each mowed region, 25 representative dry stubble fragments were removed for testing. Digital callipers were used to measure the diameter of stem fragments midway along their length and the height from the node at the soil line to the top of the stem. Because no fibre is derived from the roots, roots were removed. The weight of the 25 stalks was then determined. Fibre was removed from the stalk portion by hand. Fibre was cleaned by manually rubbing the stalks, and both the shive (woody part of flax plant) and fibre portions were individually weighed.

Flax plants from 1998–1999 were also evaluated for shive and fibre contents at intervals along the length of the stalk. Twenty plants were randomly selected from each region and divided into different stem classes: 1, pedicels without seed capsules, 2, from the end of the pedicel to midway along the stem, 3, from midway along the stem to within 10 cm of the mowed end; 4, the last 10 cm above the mowed end. For some plants a section 5 was collected consisting of the bottommost 6.35 cm above the root node representative of the stubble. The sections were freeze-dried, and weighed and the percentage of the total plant weight was determined for each section.

To evaluate the enzymatic rettability of stem sections in 1998–1999, 12 plants were randomly selected from each of regions 1, 2, 5 and 6 and sectioned as described above (sections 1–4 for regions 5 and 6 and sections 1–5 for regions 1 and 2). These segments (10 cm) were excised from sections from each of the 12 plants for enzymatic retting tests as described by Henriksson *et al*.[14] Viscozyme L, a pectinase-rich commercial enzyme product from Novozyme (Franklinton, NC, USA), was added at 0.05% (v/v) as supplied with 50 mM ethylenediaminetetraacetic acid (EDTA) to tubes containing the 12 (10 cm) segments for enzymatic retting. The sealed tubes were incubated in a rotating device at 40 °C for 24 h. Using the Fried test, stems were then rated for retting from 0 (no retting) to 3 (full fibre separation from stems) by two independent scorers and the results were averaged.[14,15] After retting and scoring, all fibres were collected from stems (those fibres not completely separated were manually removed), freeze-dried and weighed and the fibre content was determined. For regions 1–4 the amount of soluble components from a similar set of fibres from the stem sections was determined by weighing the initial unretted stems and the combined non-soluble fibre plus shive materials from stems enzymatically retted as described previously. Soluble material was calculated as: (original weight − weight of retted fibre plus residual shive)/original weight.

Climatological data for South Carolina were collected from the National Oceanic and Atmospheric Administration (NOAA). Weather conditions, temperature and rainfall were collected at Florence, SC for the 1990–1991 and 1991–1992 studies.[16] Weather conditions, temperature and rainfall from the surrounding Florence, Kingstree, Conway and Lake City area[16] were averaged to approximate conditions in the flax field from 1 September 1998 to 1 June 1999.

RESULTS

In 1990–1991, average maximum and minimum air temperatures were above normal in each month except January, when the mean maximum temperature was below normal. Rainfall totalled 617 mm and was

below normal except during January and March. In 1991–1992, rainfall totalled 618 mm and was below normal. Average maximum air temperatures during November, January, April, May and June were below normal levels. In 1998–1999 during the flax growing season, both mean maximum and minimum temperatures were above 30 year averages. Precipitation totalled 662 mm. Although crop moisture requirements are site-and year-specific, the total rainfall for 1990–1991, 1991–1992 and 1998–1999 was comparable to the 700 mm reported by Sharma and Van Sumere.[1]

Fertiliser, seeding rate, dry plant yield, plant height and stubble height are shown for harvests locations in 1990–1991, 1991–1992 and 1998–1999 in Tables 1 and 2. Seeding flax at three levels (67, 101 and 134 kg ha^{-1}) and at one fall/spring fertilizer level of 28/56 kg ha^{-1} produced dry plant yields in 1990–1991 of up to 5484 kg ha^{-1}. At this same nitrogen level, seeding flax at 67 kg ha^{-1} yielded 4609 kg ha^{-1}. A higher seeding rate generally increased dry plant yield. In 1990–1991, planting flax seeds (112 kg ha^{-1}) with fall/spring fertilizer applications of 28/0, 28/28, 28/56 and 28/84 kg ha^{-1} produced dry plant yields of up to 5910 kg ha^{-1} in 216 days. Flax grown at this same seeding rate and the 28/0 kg ha^{-1} nitrogen level resulted in a dry plant yield of 4885 kg ha^{-1}. Flax yields generally improved with increased spring nitrogen

Table 1. Harvest data for 'Ariane' flax during 1990–1991 and 1991–1992 in northeastern South Carolina

Year	Location[a]	N fertiliser (fall/spring) (kg ha^{-1})	Seeding rate (kg ha^{-1})	Early-harvest yield[b] (dry) (kg ha^{-1})	Late-harvest yield[b] (dry) (kg ha^{-1})	Plant height[c] (cm)
1990–1991	Florence	28/56	67	4508b	4609b	100a
1990–1991	Florence	28/56	101	5136a	5147ab	98b
1990–1991	Florence	28/56	134	5181a	5484a	97b
1991–1992	Florence	28/56	67	4652b	6922a	91b
1991–1992	Florence	28/56	101	5328a	7272a	95a
1991–1992	Florence	28/56	134	5063ab	7343a	89b
1990–1991	Florence	28/0	112	4690b	4885b	98b
1990–1991	Florence	28/28	112	5720a	5458ab	100ab
1990–1991	Florence	28/56	112	5813a	5910a	102a
1990–1991	Florence	28/84	112	5046b	5456ab	99b
1991–1992	Florence	28/0	112	4324b	6042b	88bc
1991–1992	Florence	28/28	112	5339a	6531a	92a
1991–1992	Florence	28/56	112	5563a	6491a	90ab
1991–1992	Florence	28/84	112	5524a	6162ab	86c

* Values followed by different letters within columns are significantly different, $P < 0.05$, according to Duncan's new multiple range test.
[a] Crop grown and harvested at the Pee Dee Research and Education Center in Florence, SC.
[b] Yield was based on the dried weight of the flax stalk excluding roots. Flax was grown in 1990–1991 for 149 days (early harvest) and 216 days (late harvest) and in 1991–1992 for 153 days (early harvest) and 211 days (late harvest).
[c] Plant height was measured at two random locations in each plot immediately prior to the harvest at seed maturity.

Table 2. Commercial harvest data for 'Ariane' flax during 1998–1999 in northeastern South Carolina

Plot[a]	N fertiliser (fall/spring) (kg ha^{-1})	Seeding rate (kg ha^{-1})	Yield[b] (dry) (kg ha^{-1})	Plant height (cm)	Stubble height (cm)
Early harvest (5 May 1999)					
Region 1	13.3/55.1	101	4418 ± 1204	86.4 ± 3.9	8.3 ± 0.4
Region 2	13.3/55.1	101	3383 ± 661	84.7 ± 0.8	8.0 ± 0.3
Region 3	13.3/55.1	101	4894 ± 852	90.6 ± 5.6	7.1 ± 0.5
Region 4	13.3/55.1	101	3608 ± 653	81.3 ± 2.9	6.6 ± 0.4
Mean			4076 ± 415	85.7 ± 1.9	7.6 ± 0.2
Late harvest (27 May 1999)					
Region 5	13.3/55.1	101	4871 ± 830	89.7 ± 5.2	6.0 ± 0.3
Region 6	13.3/55.1	101	3752 ± 173	80.4 ± 3.4	6.9 ± 0.4
Region 7	13.3/55.1	101	7048 ± 2047	97.4 ± 2.2	7.3 ± 0.3
Region 8	13.3/55.1	101	4631 ± 511	85.5 ± 3.4	7.6 ± 0.4
Mean			5076 ± 607	88.3 ± 2.4	7.1 ± 0.2

* Values are mean ± standard error of mean.
[a] Crop grown and harvested on a private farm in Nesmith, SC.
[b] Yield was based on the dried weight of the entire flax stalk including roots and seeds. Flax was grown for 142 days (early harvest) and 164 days (late harvest).

applications. Replicating the three seeding rates and four nitrogen application rates in 1991–1992 resulted in the same crop yield trends as found in 1990–1991. The 101 kg ha^{-1} seeding rate and 56 kg ha^{-1} spring N rate generally produced optimal straw yields.

In 1990–1991, small plots of flax grown for 149 (early harvest) or 216 (late harvest) days produced dry stem yields of up to 5813 and 5910 kg ha^{-1} respectively. These yields were confirmed in 1991–1992, with small plots of flax grown for 153 (early harvest) or 211 (late harvest) days producing dry stem yields of up to 5563 and 7343 kg ha^{-1} respectively. Flax grown on the commercial farm in 1998–1999 produced different yields for regions and maturities of harvest. The four regions representing young harvest (142 days of growth) produced dry stem yields averaging 3383 kg ha^{-1}, while mature plants grown for 164 days averaged 7050 kg ha^{-1} for all four regions. Within each of the maturities, however, significant variations occurred in stalk yield and plant height (Table 2), with samples indicated by regions 3 (young) and 7 (mature) having substantially higher yields and taller plants. Total dry weight yield was 4576 kg ha^{-1} for all regions and maturities, with an average stalk height of 87 cm. The mean stubble height after drum mowing in 1998–1999 was 7.1 cm. Using a mean stalk height of 87 cm, this stubble accounted for about 8% of the flax height above the ground. Based on stalk height, stubble percentage and dry weight plant yield, 374 kg ha^{-1} of the flax stalk remained in the field after drum mowing.

Stem characteristics and *in vitro* enzymatic rettability along the length of pulled plants are listed in Table 3. The upper sections of the stems contained more material soluble in the enzyme formulation. Enzymatic retting separated most fibres from stems, but, with the exception of poor retting in the pedicel, the rettability declined down the length of the stalk. From the Fried test, fibre and shive contents within the various sections were estimated from the solubility and the percentage of fibres separated and weighed. Using these calculations from the selected regions, the fibre content in stems averaged 32.6%. Fried test results indicated that differences existed between harvest times, with an early harvest (regions 1 and 2) producing a Fried score of 2.47 compared with a late-harvest (regions 5 and 6) score of 1.45. A Fried score closer to 3 indicates that it is easier to ret and results in more complete fibre separation from the stem. The amount of fibre in stubble, ie section 5, when corrected for loss of soluble components, averaged about 3.1% of the plant (about 10% of potential fibre yield).

Laboratory results of field stubble removed from regions are listed in Table 4. Mean stubble height

Table 3. Characteristics of 'Ariane' flax stalks grown in 1998–1999 at different sections along the stem for regions 1, 2, 5 and 6

Section	Dry weight of plant[a] (%)	Soluble components[b] (%)	Fibre[c] (%)	Shive[d] (%)	Fried test[e] (score)
1 (pedicel)	17.11c	27.25a	5.44c	7.94c	1.9b
2	21.65b	17.89b	7.69b	10.79b	2.6a
3	38.68a	12.73c	12.35a	21.52a	2.5a
4	19.96bc	11.46c	5.11c	12.61b	2.0b
5 (stubble)	12.05d	12.68c	2.02d	8.68c	1.4c

Values followed by different letters within columns are significantly different, $P < 0.05$, according to Duncan's new multiple range test.
[a] Weight was based on the dried weight of the flax stem excluding roots and seeds.
[b] Calculated, after enzymatic retting according to the procedure for the Fried test, as initial weight minus the sum of fibre plus shive weights divided by initial weight.
[c] Calculated by dividing the weight of fibre remaining after enzymatic retting by initial weight of soluble plus non-soluble components of each region.
[d] Calculated by dividing the weight of shive remaining after enzymatic retting by initial weight of soluble plus non-soluble components of each region.
[e] Scored from 0 = no obvious retting to 3 = full separation of fibre from stem.

Table 4. Laboratory results of excavated field stubble from flax grown in 1998–1999

Plot	Fibre[a] (%)	Shive[a] (%)	Stubble diameter (mm)	Stubble length (mm)	Estimated stubble fibre lost to mowing[b] (%)
Early harvest (5 May 1999)					
Region 1	25 ± 1.6	75 ± 1.6	2.06 ± 0.09	57.5 ± 3.8	1.66 ± 0.16
Region 2	28 ± 2.0	72 ± 2.0	1.84 ± 0.08	71.2 ± 1.8	2.33 ± 0.15
Region 3	26 ± 1.3	74 ± 1.3	1.64 ± 0.07	48.4 ± 2.2	1.41 ± 0.13
Region 4	23 ± 1.2	77 ± 1.2	1.94 ± 0.07	67.7 ± 2.0	1.93 ± 0.09
Mean	26 ± 0.8	74 ± 0.8	1.87 ± 0.04	61.2 ± 1.6	1.84 ± 0.07
Late harvest (27 May 1999)					
Region 5	22 ± 1.4	78 ± 1.4	2.17 ± 0.09	69.0 ± 3.4	1.71 ± 0.14
Region 6	21 ± 1.2	79 ± 1.2	2.04 ± 0.08	70.3 ± 1.4	1.80 ± 0.12
Region 7	18 ± 1.1	82 ± 1.1	1.99 ± 0.11	59.0 ± 2.3	1.07 ± 0.07
Region 8	19 ± 1.1	81 ± 1.1	2.17 ± 0.10	72.6 ± 4.3	1.62 ± 0.13
Mean	20 ± 0.6	80 ± 0.6	2.10 ± 0.05	67.7 ± 1.6	1.55 ± 0.06

Values are mean ± standard error of mean.
[a] Components manually separated and fibre cleaned of all other materials. Percentages calculated from average weights of 25 stubble segments per region (excluding roots).
[b] Calculated as follows: percentage stubble as (stubble length ÷ stem height) × (% fibre) for manual separation of stems.

was 6.45 cm and mean stalk diameter was 1.98 mm. This mean stubble height agrees well with the field measurement of 7.2 cm. Stubble diameter and height were significantly larger for late-harvested flax. The significant differences in stubble length among early and late harvests represent operator influence and field preparation rather than inherent differences due to samples. Flax harvested early had a diameter of 1.87 mm and flax harvested later had a diameter of 2.10 mm. Fibre content for 25 plants, based on manual separation and cleaning of fibres, averaged about 23% for all regions (26% for early harvest and 20% for late harvest).

At harvest, combined plots were still partially green. With less than half of the regions harvested for seed, approximately 272 kg of flax seed and stalk trash were obtained. Collected seeds were improperly dried, resulting in a low seed germination rate of 14%, and a seed yield was not determined. Future seed harvests would be greater with uniform drying of the seeds and stalks.

DISCUSSION

Many individuals, companies and state and government experimental stations attempted to grow flax in the South Atlantic states prior to Robinson and Hutcheson's[17] report. These studies showed that plants often grew well initially but died with the arrival of hot and dry weather and temperatures above 24 °C. Also, extended periods of low rainfall provided unsatisfactory flax fibre yields. Few plants matured and yields were not published. Robinson and Hutcheson[17] conducted and recorded a series of flax crop experiments, since there was no recorded history of flax grown in the South Atlantic region. Only three of 13 experimental fields in Georgia, South Carolina and Tennessee yielded more than 3363 kg ha^{-1} of flax, leading Robinson and Hutcheson[17] to conclude that the South Atlantic region of the USA had little land ideally suited for summer flax production. In contrast, several decades later, Loadholt[10] and Parks et al[3] established that winter-grown fibre flax could be potentially grown in the South Atlantic region with stalk yields around 6726 kg ha^{-1}. Flax plant yield results from 1990–1991, 1991–1992 and 1998–1999 experiments in South Carolina supported the results of Loadholt[10] and Parks et al.[3]

Comparison of flax grown in 1990–1991 and 1991–1992 (small plots in Florence, SC) with that grown in 1998–1999 (large hectares in Nesmith, SC) showed similar dry plant yields between years, with later harvest times within years resulting in additional growth and higher yields (Frederick J et al, 1999, unpublished). Reported yields varied between harvest years, partly because the 1998–1999 results included the entire plant whereas the 1990–1991 and 1991–1992 results were based on cuttings, 5 cm of base stalk and root removed. As expected, flax fields harvested later produced higher yields.

Our results indicate that traditional farm equipment used for multiple crops could be utilised to produce acceptable flax yields.[12] This equipment is low cost, readily available and well understood by US farmers. When harvesting by drum mower, minor changes such as mower blade angle and tractor speed relative to the greenness of plants, as well as operator skill, likely affected cutting height and the amount of flax left in the field as stubble. As farmers gain experience with harvesting flax, stubble heights (averaging 7.2 cm in this study) should be reduced, resulting in greater fibre yields. To harvest flax for seed requires that the flax be relatively dry, because green flax may clog the combine's stripper header. Seeds collected in this combine were poorly dried and exposed to high moisture levels during drying. Flax seed can be safely stored at moisture levels of 10.5% or less.[5] This study indicates that flax fields must naturally dry or be sprayed with a desiccant to acquire a seed of higher germination.

Kaul et al[18] reported that pulling flax compared with cutting could account for a 25% gain in flax fibre plant yield. After cutting the flax stalk 5 cm above the soil surface, Rowland[19] observed that the remaining stubble and roots accounted for 16% of total flax plant yield, while Zylinski[20] stated that the root forms 7.3–13.9% of the total weight of the plant. Mowing will result in lower flax straw yields than pulling, but no one, to our knowledge, has reported less fibre yield due to mowing. Since fibres do not occur in the roots,[19] mowing may have little influence on fibre yield. In our study, mowing left 8.2–12.1% of the plant (stubble) in the field. This stubble contains 1.7–3.1% of the fibre as a percentage of the plant. Despite some minor loss of fibre yield, cost-effectiveness may indicate advantages with mowing using traditional farm equipment.

The quality, yield and cross-sectional area of flax fibres in Egypt depend upon geographical location, climatic conditions and soil conditions.[2] Elhaak et al[2] reported that low levels of soil organic matter and available nutrients and high calcium concentrations decreased flax yields and reduced the quality of fibres. In our study in South Carolina, flax maturity at harvest and soil characteristics, as evaluated after harvest, across fields in 1998–1999 contributed to important differences in crop yields.[13] The regions harvested for each maturity were not initially set up for statistical comparisons, but the large variations in plant characteristics were remarkable. Soil analyses[13] provided some explanation for the variations within the field by showing that most soil elements as well as organic matter were greater in regions 3 and 7, which produced the highest yields. In the regions resulting in poorer yields (regions 2 and 6), zinc levels tended to be lower. These results agree with Les et al,[21] who found that the yield of flax fibre was a function of the soil and climate, and Sizov,[22] who found that flax fibre quality depended upon soil and climate.

Flax crops grown in 1990–1991, 1991–1992 and 1998–1999 were all subjected to unpredictable

environmental conditions that likely stressed the plants. Robinson[4] found that rain prior to harvest caused a second growth, which did not increase fibre yields but adversely changed fibre quality. In our study, on 18 February 1999, the young flax plants had a noticeable die-back, with many of the plants having yellow colouration. At this time there was low weed infestation so that flax was not hindered by competition. With limited rainfall and decrease in moisture availability the plants were likely stressed, which possibly influenced the crop yield. After this die-back the remaining plants grew well, with no yellowing, until maturity was reached.

Early harvested flax is green and contains fine and divisible fibres that lack strength.[20] Preliminary microscopic investigations of flax grown in our study indicated that the topmost portion of the flax plant, the pedicel, is less mature and less developed than other portions of the flax stalk (Foulk J *et al*, 1999, unpublished). Zylinski[20] reported younger and finer fibres at the top of the plant, with thicker fibres near the bottom of the stem. European processing typically treats the pedicel as waste, because it is difficult to remove fibre from this portion of the stalk.[20] In our study the pedicel represented in section 1 averaged about 17% of total stem weight, with about 27% of its weight potentially soluble. Based on these data, the percentage of fibre contributed to total plant weight by the pedicel was estimated to be around 5%, with the early harvest having less fibre than mature plants. *In vitro* retting using enzymes suggested that the pedicel is less efficiently retted than more central sections of the stem. Therefore the inclusion of pedicel fibre in the total yield may hinge on cost and desired degree of cleanliness.

SUMMARY

'Ariane' fiber flax was grown along the South Carolina coastal plains under varying environmental conditions using equipment typically available on farms in the USA. Seeding rate, fertility rate and harvest time influenced crop yields, with a fixed seed depth and distribution creating a homogeneous crop. Flax harvested by drum mowing gave favourable straw yields, with stubble heights between 6.0 and 7.3 cm resulting in a fibre loss of about 3% of the plant (about 10% of potential fibre yield). Dry straw yields ranged from 3383 to 7272 kg ha^{-1}. Plant height and stem weight distribution for 1998–1999 were similar for early and late harvests. However, *in vitro* retting with pectinase-rich enzymes suggested that late harvest stems in 1998–1999 were less readily retted. For both harvest times in 1998–1999, retting efficiency declined from the top to the bottom of the stems. The pedicel fibre weight was greater in the late harvest, and this section tended to be less easily retted by enzymes in both harvests. Our yield and quality data indicate that flax has the potential to be successfully produced for fibre as a winter crop in the southeastern USA.

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